

# What can we learn from the decay of $N_X(1625)$ in molecule picture?

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Considering two molecular state assumptions, i.e. S-wave  $\bar{\Lambda} - K^-$  and S-wave  $\bar{\Sigma}^0 - K^-$  molecular states, we study the possible decays of  $\bar{N}_X(1625)$  that include  $\bar{N}_X(1625) \rightarrow K^- \bar{\Lambda}, \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$ . Our results indicate: (1) if  $\bar{N}_X(1625)$  is  $\bar{\Lambda} - K^-$  molecular state,  $K^- \bar{\Lambda}$  is the main decay modes of  $\bar{N}_X(1625)$ , and the branching ratios of the rest decay modes are tiny; (2) if  $\bar{N}_X(1625)$  is  $\bar{\Sigma}^0 - K^-$  molecular state, the branching ratio of  $\bar{N}_X(1625) \rightarrow K^- \bar{\Lambda}$  is one or two order smaller than that of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$ . Thus the search for  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  will be helpful to shed light on the nature of  $\bar{N}_X(1625)$ .

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## I. INTRODUCTION

Two years ago, BES Collaboration announced an enhancement  $\bar{N}_X(1625)$  by studying the  $K^- \bar{\Lambda}$  invariant mass spectrum in  $J/\psi \rightarrow p K^- \bar{\Lambda}$  channel [1, 2, 3]. BES Collaboration gave the rough measurement result about the mass and width of  $\bar{N}_X(1625)$ :  $m = 1500 \sim 1650$  MeV,  $\Gamma = 70 \sim 110$  MeV. Experiment also indicates that spin-parity favors  $\frac{1}{2}^-$  for  $\bar{N}_X(1625)$ , which denotes the antiparticle of  $\bar{N}_X(1625)$ .

Using the branching ratio  $B(J/\psi \rightarrow p \bar{p}) = 2.17 \times 10^{-3}$  [4] as a reference, we can deduce  $B[\bar{N}_X(1625) \rightarrow \bar{\Lambda} K^-] \sim 10\%$  if  $\bar{N}_X(1625)$  is a regular baryon and the branching ratio of  $J/\psi \rightarrow p \bar{N}_X(1625)$  should be comparable with that of  $J/\psi \rightarrow p \bar{p}$ , which shows that there exists strong coupling between  $\bar{N}_X(1625)$  and  $K^- \bar{\Lambda}$ .

This enhancement structure inspired several theoretical speculations of its underlying structure. The authors of Ref. [5] studied the S-wave  $\Lambda K$  and  $\Sigma K$  with isospin  $I = 1/2$  within the framework of the chiral  $SU(3)$  quark model by solving a resonating group method (RGM) equation. Their results show a strong attraction between the  $\Sigma$  and  $K$ , and a  $\Sigma K$  quasibound state is thus formed as a consequence with a binding energy of about 17 MeV, whereas the  $\Lambda K$  is unbound. Considering small mass difference of the  $\Lambda K$  and  $\Sigma K$  thresholds, the strong attraction between  $\Sigma$  and  $K$ , and the sizable off-diagonal matrix elements of  $\Lambda K$  and  $\Sigma K$ , they also investigated the coupled channel effect of  $\Lambda K$  and  $\Sigma K$ , and found that a sharp resonance with a mass  $M = 1669$  MeV and a width  $\Gamma = 5$  MeV [5].

Liu and Zou suggested that enhancement struc-

ture  $\bar{N}_X(1625)$  comes from the strong coupling between  $\bar{N}(1535)$  and  $K \Lambda$ . Furthermore  $R = g_{\bar{N}(1535)K\Lambda}/g_{\bar{N}(1535)p\eta}$  are extracted by the branching ratios taken from BES experiments on  $J/\psi \rightarrow \bar{p} p \eta$  [7, 8, 9] and  $J/\psi \rightarrow p K^- \bar{\Lambda}$  [1]. The new obtained value of  $g_{\bar{N}(1535)K-\bar{\Lambda}}$  is shown to reproduce recent  $pp \rightarrow p K^- \bar{\Lambda}$  near-threshold cross section data as well [6].

At recent Hadron 07 conference, BES Collaboration reported the preliminary new experiment result of  $\bar{N}_X(1625)$ . Its mass and width are well determined as [10]

$$m = 1625_{-7}^{+5+13} \text{ MeV}, \quad \Gamma = 43_{-7}^{+10+28} \text{ MeV}$$

respectively. The production rate of  $\bar{N}_X(1625)$  is

$$B[J/\psi \rightarrow p \bar{N}_X(1625)] \cdot B[\bar{N}_X(1625) \rightarrow K^- \bar{\Lambda}] = 9.14_{-1.25-8.28}^{+1.30+4.24} \times 10^{-5}.$$

These more accurate experimental information of  $\bar{N}_X(1625)$  provides us good chance to further study the nature of  $\bar{N}_X(1625)$ .

Despite two theoretical speculations proposed above, at present the study of decays of  $\bar{N}_X(1625)$ , which play an important role to clarify the properties of  $\bar{N}_X(1625)$ , is missing. In this work, we firstly assume  $\bar{N}_X(1625)$  to be a molecular state and is dedicated to the study of the possible decays of  $\bar{N}_X(1625)$ . For the convenience of comparing with BES experiment, one focuses on the study of decays of antiparticle  $\bar{N}_X(1625)$  with the spin-parity  $\frac{1}{2}^+$ .

This paper is organized as follow. In Sect. II, we present the formulation about the possible decays of  $\bar{N}_X(1625)$ . In Sect. III, the numerical results are given. The last section is the conclusion and discussion.

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## II. FORMULATION

In this work we do not focus on whether  $\bar{\Lambda} - K^-$  or  $\bar{\Sigma}^0 - K^-$  can form S-wave molecular state, which is investigated in Ref. [5]. Whereas we are mainly dedicated to the study of possible decays of  $\bar{N}_X(1625)$  in two different assumptions of molecular states.

### A. The possible decays assuming $\bar{N}_X(1625)$ to be $\bar{\Lambda} - K^-$ molecular state

In the assumption of  $\bar{\Lambda} - K^-$  molecular state, the most direct decay mode of  $\bar{N}_X(1625)$  is  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} + K^-$  depicted in Fig. 1 (a). Its decay amplitude is

$$\mathcal{M}[\bar{N}_X(1625) \rightarrow \bar{\Lambda} + K^-] = i\mathcal{G}\bar{v}_N\gamma_5 v_{\bar{\Lambda}}, \quad (1)$$

where  $\mathcal{G}$  is the coupling constant between  $\bar{N}_X(1625)$  and  $\bar{\Lambda}K^-$ .  $v_{\bar{\Lambda}}$  and  $v_N$  are the spinors.

Besides the direct decay, there are several subordinate decays depicted in Fig. 1 (c)-(e) by the final state interaction (FSI) effect. For obtaining their decay amplitudes, one needs to use the below Lagrangians [12, 13]:

$$\mathcal{L}_{\mathcal{P}\mathcal{P}\mathcal{V}} = -ig_{\mathcal{P}\mathcal{P}\mathcal{V}}Tr([\mathcal{P}, \partial_\mu \mathcal{P}]\mathcal{V}^\mu), \quad (2)$$

$$\mathcal{L}_{\mathcal{B}\mathcal{B}\mathcal{P}} = F_P Tr(\mathcal{P}[\mathcal{B}, \bar{\mathcal{B}}])\gamma_5 + D_P Tr(\mathcal{P}\{\mathcal{B}, \bar{\mathcal{B}}\})\gamma_5, \quad (3)$$

$$\mathcal{L}_{\mathcal{B}\mathcal{B}\mathcal{V}} = F_V Tr(\mathcal{V}^\mu[\mathcal{B}, \bar{\mathcal{B}}])\gamma_\mu + D_V Tr(\mathcal{V}^\mu\{\mathcal{B}, \bar{\mathcal{B}}\})\gamma_\mu, \quad (4)$$

where the concrete values of the coupling constants will be given in detail in the following section.  $\bar{\mathcal{B}}$  is the Hermitian conjugate of  $\mathcal{B}$ .  $\mathcal{P}$ ,  $\mathcal{V}$  and  $\mathcal{B}$  respectively denote the octet pseudoscalar meson, the nonet vector meson and baryon matrices:

$$\mathcal{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{3}\eta \end{pmatrix},$$

$$\mathcal{V} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix},$$

$$\mathcal{B} = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^{*-} & \bar{\Xi}^{*0} & \frac{-2\Lambda}{\sqrt{6}} \end{pmatrix}.$$

Because  $M_{\bar{\Lambda}} + M_{K^-}$  is about 1610 MeV, which is less than the mass of  $\bar{N}_X(1625)$ , thus intermediate states  $\bar{\Lambda}$  and  $K^-$  in Fig. 1 (b)-(d) can be on-shell. By Cutkosky cutting rules, one writes out the general amplitude ex-

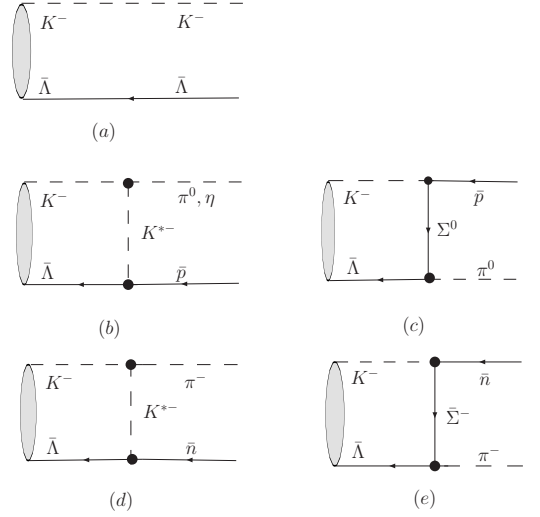


FIG. 1: The diagrams depicting the decays of  $\bar{N}_X(1625)$  in the picture of  $\bar{\Lambda} - K^-$  molecular state.

pression corresponding to Fig. 1 (b), (d)

$$\begin{aligned} \mathcal{M}_1^{(\mathcal{A}_1, \mathcal{C}_1)} &= \frac{1}{2} \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} \\ &\times (2\pi)^4 \delta^4(M_N - p_1 - p_2) [i\mathcal{G}\bar{v}_N\gamma_5 v_{\bar{\Lambda}}] \\ &\times [ig_1 \bar{v}_{\bar{\Lambda}} \gamma_\mu v_{\mathcal{A}_1}] [ig_2 (p_1 + p_3)_\nu] \frac{i}{q^2 - M_{\mathcal{C}_1}^2} \\ &\times \left[ -g^{\mu\nu} + \frac{q^\mu q^\nu}{M_{\mathcal{C}_1}^2} \right] \mathcal{F}^2(M_{\mathcal{C}_1}, q^2). \end{aligned} \quad (5)$$

For Fig. 1 (c), (e), the general amplitude expression is

$$\begin{aligned} \mathcal{M}_1^{(\mathcal{A}_2, \mathcal{C}_2)} &= \frac{1}{2} \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} \\ &\times (2\pi)^4 \delta^4(M_N - p_1 - p_2) [i\mathcal{G}\bar{v}_N\gamma_5 v_{\bar{\Lambda}}] \\ &\times [ig'_2 \bar{v}_{\bar{\Lambda}} \gamma_5] \frac{i(\not{q} + M_{\mathcal{C}_2})}{q^2 - M_{\mathcal{C}_2}^2} [ig'_1 \gamma_5 v_{\mathcal{A}_2}] \\ &\times \mathcal{F}^2(M_{\mathcal{C}_2}, q^2). \end{aligned} \quad (6)$$

In the above expressions,  $\mathcal{C}_i$  and  $\mathcal{A}_i$  denote the exchanged particle and the final state baryon respectively.  $p_1$  and  $p_2$  are respectively the four momenta of  $K^-$  and  $\bar{\Lambda}$ .  $\mathcal{F}^2(m_i, q^2)$  etc denotes the form factor which compensates the off-shell effects of hadrons at the vertices. In this work, one takes  $\mathcal{F}^2(m_i, q^2)$  as the monopole form [15, 16]

$$\mathcal{F}^2(m_i, q^2) = \left( \frac{\xi^2 - m_i^2}{\xi^2 - q^2} \right)^2, \quad (7)$$

where  $\xi$  is a phenomenological parameter. As  $q^2 \rightarrow 0$  the form factor becomes a number. If  $\xi \gg m_i$ , it becomes unity. As  $q^2 \rightarrow \infty$ , the form factor approaches to zero. As the distance becomes very small, the inner

structure would manifest itself and the whole picture of hadron interaction is no longer valid. Hence the form factor vanishes and plays a role to cut off the end effect. The expression of  $\xi$  is [16]

$$\xi(m_i) = m_i + \alpha \Lambda_{QCD}, \quad (8)$$

where  $m_i$  denotes the mass of exchanged meson.  $\Lambda_{QCD} = 220$  MeV.  $\alpha$  is a phenomenological parameter and is of order unity.

### B. The decay modes assuming $\bar{N}_X(1625)$ to be a $\bar{\Sigma}^0 - K^-$ molecular state

Because of having no enough phase space,  $\bar{N}_X(1625)$  can not decay to  $\bar{\Sigma}^0$  and  $K^-$ .

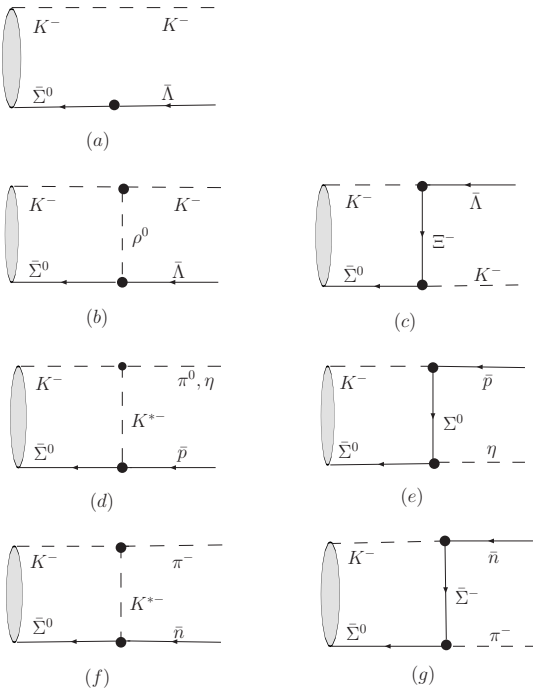


FIG. 2: The diagrams depicting the decays of  $\bar{N}_X(1625)$  in the assumption of  $\bar{\Sigma}^0 - K^-$  molecular state for  $\bar{N}_X(1625)$ .

Isospin violation effect can result in the mixing of  $\Sigma$  with  $\Lambda^0$  [11]. Thus decay  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} + K^-$  occurs, which is depicted by Fig. 2 (a). Using the Lagrangian

$$\mathcal{L}_{\text{mixing}} = g_{\text{mixing}} (\bar{\psi}_{\Sigma^0} \psi_{\Lambda} + \bar{\psi}_{\Lambda} \psi_{\Sigma^0})$$

with the coupling constant  $\theta = 0.5 \pm 0.1$  MeV obtained by QCD sum rule [11], one obtains the decay amplitude

$$\mathcal{M}[\bar{N}_X(1625) \rightarrow \bar{\Sigma}^0 + K^-] = \mathcal{G} g_{\text{mixing}} \bar{v}_N \gamma_5 \frac{i}{\not{p} - M_{\Lambda}} v_{\bar{\Lambda}},$$

where  $p$  and  $M_{\Lambda}$  are the four momentum and mass carried by  $\bar{\Lambda}$ .

For the decays depicted in Fig. 2 (b)-(g),  $\bar{\Sigma}^0$  and  $K^-$  are off-shell. Thus the general expression of Fig. 2 (b), (d), (f) is expressed as

$$\begin{aligned} \mathcal{M}_3^{(\mathcal{A}_3, \mathcal{C}_3)} &= \int \frac{d^4 q}{(2\pi)^4} [i\mathcal{G} \bar{v}_N \gamma_5] \frac{i}{-\not{p}_2 - M_{\bar{\Sigma}^0}} [ig_3 \gamma_{\mu} v_{\mathcal{A}_3}] \\ &\times [ig_4 (p_1 + p_3)_{\nu}] \frac{-ig^{\mu\nu}}{q^2 - M_{\mathcal{C}_3}^2} \frac{i}{p_1^2 - M_K^2} \\ &\times \mathcal{F}^2(M_{\mathcal{C}_3}, q^2), \end{aligned} \quad (10)$$

for Fig. 2 (c), (e), (g) the general amplitude expression reads as

$$\begin{aligned} \mathcal{M}_4^{(\mathcal{A}_4, \mathcal{C}_4)} &= \int \frac{d^4 q}{(2\pi)^4} [i\mathcal{G} \bar{v}_N \gamma_5] \frac{i(\not{p}_2 - M_{\bar{\Sigma}^0})}{-p_2^2 - M_{\bar{\Sigma}^0}^2} [ig'_4 \gamma_5] \\ &\times \frac{i(\not{q} + M_{\mathcal{C}_4})}{q^2 - M_{\mathcal{C}_4}^2} [ig'_3 \gamma_5 v_{\mathcal{A}_4}] \\ &\times \frac{i}{p_1^2 - M_K^2} \mathcal{F}^2(M_{\mathcal{C}_4}, q^2), \end{aligned} \quad (11)$$

where  $p_1$  and  $p_2$  denote the four momenta carried by  $K^-$  and  $\bar{\Sigma}^0$  respectively.  $q = p_1 - p_3 = p_4 - p_2$ . The definition of  $\mathcal{F}^2(m_i, q^2)$  is given in eq. (7). Moreover the form factor may provide a convergent behavior for the triangle loop integration. That is very similar to the case of the Pauli-Villas renormalization scheme [17, 18].

Using the same treatment in Ref. [19], we obtain the further expressions of eqs. (10) and (11) that are listed in appendix.

### III. NUMERICAL RESULTS

In QCD sum rule approach, the ratios of coupling constants in eqs. (3) and (4) are given as  $F_P/D_P = 0.6$  [20] and ratio  $F_V/(F_V + D_V) = 1$  [21]. In the limit of SU(3) symmetry, by  $g_{NN\pi} = 13.5$  and  $g_{NN\rho} = 3.25$  [22], one obtains the meson-baryon coupling constants relevant to our calculation:  $g_{PPV} = 6.1$ ,  $F_P = 13.5$ ,  $D_P = 0$ ,  $F_V = 1.2$ ,  $D_V = 2.0$ .

Using the above parameters as input, we get the ratios of the decay widths of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  to the decay width of  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} K^-$  in the assumptions of  $\bar{\Lambda} - K^-$  molecular state and  $\bar{\Sigma}^0 - K^-$  molecular state for  $\bar{N}_X(1625)$ , which are shown in Fig. 3 and Fig. 4 respectively. Here  $\alpha$  in the form factor is taken as the range  $1 \sim 3$  [16].

Fig. 3 and Fig. 4 show that these ratios do not strongly depend on the  $\alpha$ . By taking a typical value  $\alpha = 1.5$ , one further gives the following ratios listed in Table I.

(9) By using these ratios shown in Figs. 3, 4 and the branching ratio  $B[J/\psi \rightarrow p \bar{N}_X(1625)] \cdot B[\bar{N}_X(1625) \rightarrow K^- \bar{\Lambda}] = 9.14_{-1.25}^{+1.30+4.24}_{-8.28} \times 10^{-5}$  given by BES [10], one estimates the branching ratio of subordinate decays of

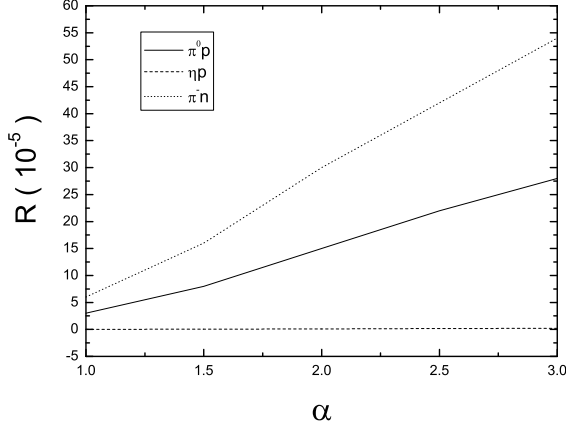


FIG. 3: The ratios of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  decay widths to  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} K^-$  decay width in the picture of  $\bar{\Lambda} - K^-$  molecular state.

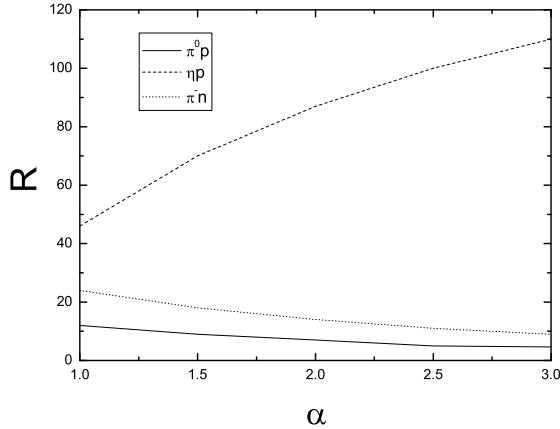


FIG. 4: The ratios of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  decay widths to  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} K^-$  decay width in  $\bar{\Sigma}^0 - K^-$  molecular state picture.

$\bar{N}_X(1625)$  in  $J/\psi$  decay shown in Table. II. Due to the uncertainty of  $\alpha$ , thus we given the possible ranges for these branching ratios.

If  $\bar{N}_X(1625)$  is  $\bar{\Lambda} - K^-$  molecular state,  $\bar{N}_X(1625)$  mainly decay to  $K^- \bar{\Lambda}$ . The branching ratios of the subordinate decays  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  are far less than that of  $\bar{N}_X(1625) \rightarrow K^- \bar{\Lambda}$ , which can explain why  $\bar{N}_X(1625)$  was firstly observed in the mass spectrum of  $K^- \bar{\Lambda}$ . In the Particle Data Book [4], the smallest branching ratios that have been measured for  $J/\psi$  decays are larger than  $10^{-5}$ . Thus the rest decays of  $\bar{N}_X(1625)$  is

	$\frac{\Gamma(\pi^0 \bar{p})}{\Gamma(K^- \bar{\Lambda})}$	$\frac{\Gamma(\eta \bar{p})}{\Gamma(K^- \bar{\Lambda})}$	$\frac{\Gamma(\pi^- \bar{n})}{\Gamma(K^- \bar{\Lambda})}$
$\bar{\Lambda} - K^-$	$1 \times 10^{-4}$	$5 \times 10^{-7}$	$2 \times 10^{-4}$
$\bar{\Sigma}^0 - K^-$	9	70	18

TABLE I: The ratios of the decay widths of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  to the decay width of  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} K^-$  in different molecular assumptions with  $\alpha = 1.5$ .

hardly measured in further experiments.

If  $\bar{N}_X(1625)$  is S-wave  $\bar{\Sigma}^0 - K^-$  molecular state,  $\bar{N}_X(1625)$  can not decay to  $\bar{\Sigma}^0 K^-$  due to having no enough phase space. Because of the  $\Lambda - \Sigma^0$  mixing mechanism and final state interaction effect,  $\bar{N}_X(1625)$  can decay to  $\bar{\Lambda} K^-$ . Our calculations indicate that the branching ratio of  $\bar{N}_X(1625) \rightarrow \bar{\Lambda} K^-$  is about one or two order smaller than that of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$ . Although the neutral particles in the decay modes  $\pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  increase the difficulty of searching these decay modes in experiment, future experiments still have the potential to find  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$ .

#### IV. DISCUSSION AND CONCLUSION

In this work, we focus on different results of the decay mode of  $\bar{N}_X(1625)$  resulted from two molecule assumptions, i.e. S-wave  $\bar{\Lambda} - K^-$  and S-wave  $\bar{\Sigma}^0 - K^-$  systems. Basing on these two pictures, we estimate the possible decay modes of  $\bar{N}_X(1625)$ , which include  $K^- \bar{\Lambda}$ ,  $\pi^0 \bar{p}$ ,  $\eta \bar{p}$  and  $\pi^- \bar{n}$ . Our result indicates that the search for  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  will shed light on the nature of  $\bar{N}_X(1625)$ .

At present the experimental information indicates that  $\bar{N}_X(1625)$  is of very strong coupling with  $\bar{\Lambda} K^-$ , and other modes is still missing [10]. Thus the assumption of S-wave  $\bar{\Lambda} - K^-$  molecular state is more favorable than that of S-wave  $\bar{\Sigma}^0 - K^-$  molecular state for  $\bar{N}_X(1625)$ . However, the result of Ref. [5] indicates that it is difficult to form a  $\Lambda K$  bound state. In fact, in molecule picture, in general such an S-wave  $\bar{\Lambda} K^-$  system should be of very wide width, which contradicts with the experimental information of  $\bar{N}_X(1625)$  ( $\Gamma_{\bar{N}_X(1625)} = 43$  MeV). Although the above analysis shows that S-wave  $\bar{\Lambda} - K^-$  molecule assignment as  $\bar{N}_X(1625)$  is not suitable, we still try to study the decay of  $\bar{N}_X(1625)$  in S-wave  $\bar{\Lambda} - K^-$  molecule picture.

In the assumption of S-wave  $\bar{\Sigma}^0 - K^-$  molecular state, the sum of branching ratios of  $\bar{N}_X(1625) \rightarrow \pi^0 \bar{p}, \eta \bar{p}, \pi^- \bar{n}$  listed in Table II is about  $10^{-2}$ . Such large branching ratio is unreasonable for  $J/\psi$  decay. BES collaboration has already studied  $J/\psi \rightarrow p \pi^- \bar{n}$  in Ref. [8] and  $J/\psi \rightarrow p(\eta \bar{p})$  in Ref. [9]. The branching ratios respectively corresponding to  $J/\psi \rightarrow p \pi^- \bar{n}$  and  $J/\psi \rightarrow p \eta \bar{p}$  are  $2.4 \times 10^{-3}$  and  $2.1 \times 10^{-3}$  [8, 9]. Although these experimental values is comparable with our numerical result of corresponding channel, experiments did not find structure consistent with  $\bar{N}_X(1625)$ , which seem to show that

evidence against S-wave  $\bar{\Sigma}^0 - K^-$  molecular picture is gradually accumulating. However we still urge our experimental colleague carefully analyze  $J/\psi \rightarrow p\pi^-\bar{n}$  and  $J/\psi \rightarrow p\eta\bar{p}$  channel in further experiments, especially forthcoming BESIII.

Thus the above analysis shows that the pure molecular state structure seems to be very difficult to explain  $N_X(1625)$ .

We note that there exist two well established states  $N^*(1535)$  and  $N^*(1650)$  with  $J^P = 1/2^-$  nearby the mass of  $N_X(1625)$ . In PDG [4], the branching ratio

of  $N^*(1650) \rightarrow K\Lambda$  is about  $3 \sim 11\%$ . The authors of Ref. [6] indicated that  $N^*(1535)$  should have large  $s\bar{s}$  component in its wave function which shows the large  $N^*(1535)K\Lambda$  coupling.  $N^*(1535)$  and  $N^*(1650)$  can strongly couple to  $K\Lambda$ . Thus, before confirming  $N_X(1625)$  to be a new resonance, theorists and experimentalists of high energy physics need to carry out co-operation to answer whether  $N_X(1625)$  enhancement is related to  $N^*(1535)$  and  $N^*(1650)$ . Forthcoming BESIII and HIRFL-CSR will provide the good place to further understand  $N_X(1625)$  structure.

	$\bar{\Lambda} - K^-$ system	$\bar{\Sigma}^0 - K^-$ system
$J/\psi \rightarrow p\bar{N}_X(1625) \rightarrow p(\pi^0\bar{p})$	$1 \times 10^{-8} \sim 3 \times 10^{-8}$	$\sim 1 \times 10^{-3}$
$J/\psi \rightarrow p\bar{N}_X(1625) \rightarrow p(\eta\bar{p})$	$4 \times 10^{-11} \sim 2 \times 10^{-10}$	$\sim 7 \times 10^{-3}$
$J/\psi \rightarrow p\bar{N}_X(1625) \rightarrow p(\pi^-\bar{n})$	$2 \times 10^{-8} \sim 5 \times 10^{-8}$	$\sim 2 \times 10^{-3}$

TABLE II: The branching ratios of subordinate decays of  $\bar{N}_X(1625)$  in two different molecular state pictures.

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### Appendix

The further expressions of eqs. (10) and (11) are

$$\begin{aligned}
\mathcal{M}_3^{(A_3, C_3)} = & -g_3 g_4 \mathcal{G} \int_0^1 dx \int_0^{1-x} dy \left\{ \left[ \frac{(\xi^2 - M_{\bar{C}_3}^2)y}{16\pi^2 \Delta^2(M_K, M_{\bar{\Sigma}^0}, \xi)} - \frac{1}{16\pi^2 \Delta(M_K, M_{\bar{\Sigma}^0}, M_{C_3})} \right. \right. \\
& + \left. \frac{1}{16\pi^2 \Delta(M_K, M_{\bar{\Sigma}^0}, \xi)} \right] \bar{v}_N \gamma_5 \left[ \not{p}_4 \not{p}_3 [2 - 2x - (1 - x - y) + (1 - x - y)x] \right. \\
& + \not{p}_3 \not{p}_3 [2(1 - x - y) - (1 - x - y)^2] + \not{p}_4 \not{p}_4 (x - x^2) + \not{p}_3 \not{p}_4 (1 - x - y)x \\
& + \left. \not{p}_3 [2M_{\bar{\Sigma}^0} - (1 - x - y)M_{\bar{\Sigma}^0}] + \not{p}_4 x M_{\bar{\Sigma}^0} \right] \bar{v}_{A_3} \Big\} \\
& - g_3 g_4 \mathcal{G} \int_0^1 dx \int_0^{1-x} dy \left\{ \left[ \frac{2}{(4\pi)^2} \log \left( \frac{\Delta(M_K, M_{\bar{\Sigma}^0}, \xi)}{\Delta(M_K, M_{\bar{\Sigma}^0}, M_{C_3})} \right) - \frac{(\xi^2 - M_{\bar{C}_3}^2)y}{8\pi^2 \Delta(M_K, M_{\bar{\Sigma}^0}, \xi)} \right] \right. \\
& \times \left. \left[ \bar{v}_N \gamma_5 \left( -\frac{1}{4} \right) \gamma_\mu \gamma^\mu v_{A_3} \right] \right\}, \tag{12}
\end{aligned}$$

$$\begin{aligned}
\mathcal{M}_4^{(A_4, C_4)} = & -g'_3 g'_4 \mathcal{G} \int_0^1 dx \int_0^{1-x} dy \left\{ \left[ \frac{(\xi^2 - M_{C_4}^2)y}{16\pi^2 \Delta^2(M_K, M_{\Sigma^0}, \xi)} - \frac{1}{16\pi^2 \Delta(M_K, M_{\Sigma^0}, M_{C_4})} \right. \right. \\
& + \left. \frac{1}{16\pi^2 \Delta(M_K, M_{\Sigma^0}, \xi)} \right] \bar{v}_N \gamma_5 \left[ \not{p}_4 \not{p}_3 [(1-x-y) - (1-x-y)x] \right. \\
& + \not{p}_3 \not{p}_3 (1-x-y)^2 + \not{p}_4 \not{p}_4 (x^2 - x) - \not{p}_3 \not{p}_4 (1-x-y)x \\
& + \left. \not{p}_3 [-M_{\Sigma^0}(1-x-y) + (1-x-y)M_{C_4}] - \not{p}_4 x(M_{C_4} - M_{\Sigma^0}) + \not{p}_4 M_{C_4} - M_{\Sigma^0} M_{C_4} \right] v_{A_4} \left. \right\} \\
& - g'_3 g'_4 \mathcal{G} \int_0^1 dx \int_0^{1-x} dy \left\{ \left[ \frac{2}{(4\pi)^2} \log \left( \frac{\Delta(M_K, M_{\Sigma^0}, \xi)}{\Delta(M_K, M_{\Sigma^0}, M_{C_4})} \right) - \frac{(\xi^2 - M_{C_4}^2)y}{8\pi^2 \Delta(M_K, M_{\Sigma^0}, \xi)} \right] \right. \\
& \times \left. \left[ \bar{v}_N \gamma_5 \frac{1}{4} \gamma_\mu \gamma^\mu v_{A_4} \right] \right\}, \tag{13}
\end{aligned}$$

where

$$\begin{aligned}
\Delta(a, b, c) = & m_3^2(1-x-y)^2 - 2(p_3 \cdot p_4)(1-x-y)x \\
& + m_4^2 x^2 - (m_3^2 - a^2)(1-x-y) \\
& - (m_4^2 - b^2)x + yc^2,
\end{aligned}$$

$m_3(m_4)$  and  $p_3(p_4)$  are the masses and four- momenta of the final states.

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